GCM monthly data is based on ensemble climate simulations covering this period, and represent a subset of data from runs that span the entire half century since 1950. Two different models are analyzed, one referred to as MRF9 and described in Kumar et al. (1996), and the other referred to as CCM3 and described in Hack et al. (1998). Both GCMs are run at a T42 spectral resolution with 18 sigma layers, and each has been forced with the observed monthly evolving global SSTs. An 18-member ensemble has been generated for MRF9, while a 12-member ensemble has been generated for CCM3, with each member subjected to identical SST evolution but starting from different atmospheric initial conditions. The ensemble average of the model simulations are shown, and model anomalies are calculated relative to the respective GCMs' climatology.

3. Results

The observed monthly evolution of zonal mean 200 hPa heights, tropical rainfall, and tropical SSTs for the period January 1997-January 2000 is shown in Fig. 1. The feature of principal interest is the band of persistent positive height anomalies between 30-45 degrees latitude of both hemispheres that develops in spring 1998, which is indicative of a tropospheric warming. The midlatitude atmospheric warming in the NH was accompanied by strong surface warming, in particular over Eurasia and North America (see Fig. 5a).

The impression gained from the left hand panel is of a coherent poleward shift of the tropospheric warming, developing first in tropical latitudes in association with the 1997 El Niño, and then persisting in the middle latitudes during the extended La Niña that developed in spring 1998. As we will show, however, this intriguing time history of atmospheric anomalies is by-and-large inconsistent with the time evolution of the atmospheric signal related to ENSO SSTs.

To illustrate the strong zonal and axial symmetry of the climate anomalies during this period, Fig. 2 (top panel) presents the spatial pattern of the observed 200 hPa height anomalies during January-December 1999. All longitudes in the midlatitudes experienced tropospheric warming as indicated by the strongly uniform distribution of above normal heights, and it is clear that the zonally averaged anomalies of Fig. 1 indeed reflect a symmetric mode rather than a statistical residual of regional variability. Related to the changed thermal structure implied by Fig. 2 is a systematic poleward displacement of the westerly jets in both. Also noteworthy are the below normal heights over the equatorial east Pacific reflecting La Niña's local impact. Yet, contrary to La Niña's historical signal (e.g., Lau and Nath 1994; Hoerling et al. 1997) which consists of tropical-wide below normal heights, 200 hPa heights are actually near or above normal over both the Indian and tropical Atlantic oceans during 1999. This suggests that forcing other than that associated with SSTs in the equatorial east Pacific may have been important.

To assess the role played by oceans, the lower two panels in Fig. 2 present the GCM ensemble responses to the prescribed global SSTs. Each model simulates a strong zonally symmetric tropospheric warming in the midlatitudes of both hemispheres. Indeed, the amplitude of the midlatitude height anomalies in the GCMs are similar to those observed, despite the fact that the GCM results are based on an average of 12-18 simulations spanning this period. The model anomalies are statistically significant, as will be shown further, and support the interpretation that the observed midlatitude tropospheric warming was unlikely a random occurrence of intrinsic atmospheric variability. Note also that both models capture the tropical Pacific tropospheric cooling (though weaker than observed) associated with the La Nina conditions, but that much of the remaining tropical 200 hPa heights are actually above normal.

The time history of the observed tropospheric warming is also realistically simulated in the GCMs as demonstrated in Fig. 3. Tropical 200 hPa positive height anomalies peak in early 1998 in both MRF9 (top panels) and CCM3 (bottom panel) simulations, with a subsequent axially symmetric development of positive height anomalies in midlatitudes, a feature that persists in the models throughout 1999. The onset of the midlatitude tropospheric warming signal in early 1998 coincides with a dramatic increase in precipitation over the Indian and tropical West Atlantic Oceans (Fig. 3, right side panels) that appears to be a local response to SST warming in those regions. It is common to experience a warming of those waters with about a one season lag to El Niño in the east Pacific (e.g., Yulleva and Wallace 1996). However, the strength of that warming in the vicinity of the Maritime continent where anomalies exceeded 3 standardized departures (see Fig. 1), was unusual. Furthermore, these warm SSTs persisted throughout 1999 and early 2000 despite La Niña conditions during that time.

In tandem with the tropospheric warming in midlatitudes, surface temperatures also experienced high values, especially over the northern hemisphere land masses. Figure 4 shows the longitudinal distribution of observed and simulated surface temperature anomalies during 1999. The values represent an average between 25N-55N that correspond to the belt of above normal 200 hPa heights in Fig. 2. The principal warming was observed over interior Eurasia and North America, and all longitudes expeienced warming with the exception of the eastern Pacific ocean. Warming of the land masses also occurs in the both GCMs, though with amplitudes closer to those observed over North America than over Eurasia. It is worth noting that the GCMs' 200 hPa positive height anomalies over this same latitude band closely mathches the observations, indicating a closer qunatitative match between observed and simulated columnar temperature change. Its worth noting that the observedyear-to-year variability of surface temperature and tropospheric-column temperature are not perfectly correlated, even for global values (Hurrell and Trenberth 1996), reflecting the fact that different physcial processes control surface versus free atmospheric temperature. Given the simplicity of the GCM's land processes, and the need to parameterize many of the processes maintaining surface temperature, the level of agreement between simulated and observed land temperatures in Fig. 4 is somewhat striking.

It is reasonable to argue, given the realism of responses in both GCMs, the observed circulation anomalies and the associated tropospheric warming during January 1998-January 2000 were forced by the global SSTs. The physical processes involved are unclear, however. For example, the spatial distribution of 200 hPa heights in the models, thoough similar to that observed (Fig. 2), does not resemble any of the well-known teleconnections associated with air-sea interactions (e.g., Horel and Wallace 1981, Hoskins and Karoly 1981; Wallace et al. 1990). That the oceanic control of the climate state during this period was strong is confirmed by the strong reproducibility of the zonal mean 200 hPa height anomalies among individual realizations, as shown in Fig. 5 for the 12-members of CCM3. A similar results exists for the MRF ensemble members (not shown). However, given the fact that the models were subjected to the global SST anomalies, it is unclear which SSTs were of greatest relevance.

Some insight is gained by determining the linear statistical signal associated with east equatorial Pacific SSTs. For this purpose, we have regressed monthly 200 hPa heights onto an index of ENSO given by the principal component time series of the leading empirical orthogonal function (EOF) of monthly tropical Pacific SSTs for 1950-96. Following Hoerling et al. (2000), a bi-linear analysis is performed in which regressions for ENSO warm and cold phases are calculated separately. Figure 6 shows the reconstruction of 200 hPa heights for 1997-2000 based on the observed and GCMs' ENSO signals. It is evident that a midlatitude tropospheric warming of the type observed is not consistent with ENSO forcing, and only during the peak of the 1997 El Niño is there a correspondence between the zonal mean climate anomalies and the regression signal.

4. Summary

Insights on the origin of a strong midlatitude warming in both northern and southern hemispheres during Janury 1998-January 2000 has been sought using new suites of atmospheric GCM simulations forced by global SSTs. Our analysis focused on 200 hPa heights as a proxy for tropospheric column average temperature, and also on surface temperature. The models confirm that the climate behaviour during the period reflects oceanic forcing. Indeed, our analysis of ensemble simulations indicates the sign of zonally averaged climate anomalies was deterministic in the presence of these SSTs, attesting to the strength of the boundary forced signal. Empirical analysis of observed and GCM data suggests that the tropical east Pacific SSTs were not a significant factor in the midlatitude warming, however, despite the strong ENSO cycle during the period.

We are currently performing and analyzing additional GCM experiments that seek to isolate which SSTs were instrumental in the midlatitude warming of 1998-2000. Our initial focus is on the Indo-Pacific warm pool, in part because the persistence of enhanced rainfall over this region in observations and the GCMs, and the fact that SSTs in that area reached unusally high values during the period. It is possible the high temperatures in the warm pool during 1998 and 1999 reflect an interannual transient event (though apparently unrelated to ENSO). However, SSTs is that region have been trending upward during most of the 20th Century (e.g., Levitus et al. 2000), so that longer time scale processes may also be relevant. The recent coupled atmosphere-ocean model results of Knutson et al. (1999) are interesting in this regard in that they reproduce the 20th Century warming trend of the warm pool when using time-varying radiative forcing, suggesting the observed trend is due to positive thermal forcing by enhanced greenhouse gases. Further analysis of the role of the Indo-Pacific region in atmospheric variability may thus shed light on predictability on time scales of a season and beyond.

Acknowledgments. The support offered by NOAA's Climate Dynamics and Experimental Prediction (CDEP) Program, and the NOAA-OGP GOALS program, are gratefully acknowledged. The CCM3 data were kindly provided by Maurice Blackmon, Jim

Hurrell, and Jeff Lee of NCAR's Climate and Global Dynamics Division.

5. References

Arkin, P. A., and B. N. Meisner, 1987: The relationship between large-scale convective rainfall and cloud cover over the Western Hemisphere during 1982-84. *Mon. Wea. Rev.*, **115**, 51-74.

Graham, N. E., 1995: Simulations of recent global temperature trends. *Science*, **267**, 666-671.

Hack, J. J., J. T. Kiehl, and J. W. Hurrell, 1998: The hydrologic and thermodynamic characteristics of the NCAR CCM3. *J. Climate*, **11**, 1179-1206.

Hoerling, M. P., A. Kumar, and M. Zhong, 1997: El Nino, La Nina and the nonlinearity of their teleconnections. *J. Climate*, **10**, 1769-1786.

Hoerling, M. P., A. Kumar, and T.-Y. Xu, 2000: Robustness of the nonlinear atmospheric response to opposite phases of ENSO. *J. Climate*, in press.

Horel, J. D. and J. M. Wallace, 1981: Planetary-scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev.*, **109**, 813–829.

Hoskins, B.J., and Karoly, D., 1981: The steady linear response of a spherical atmosphere to thermal and orographic forcing. *J. Atmos. Sci.*, **38**, 1179–1196.

Hurrell, J. W., and K. E. Trenberth, 1996: Satellite versus surface estimates of air temperature since 1979. *J. Climate*, **9**, 2222-2232.

Kiladis, G. N., and H. Diaz, 1989: Global climatic anomalies associated with extreme in the Southern Oscillation. *J. Climate*, **2**, 1069-1090.

Knutson, T. R., T. L. Delworth, K. W. Dixon, and R. J. Stouffer, 1999: Model assessment of regional surface temperature trends (1949-1997). *J. Geophys. Res.*, **104(D24)**, 30,981-30,996.

Kumar, A., A. Leetmaa, and M. Ji, 1994: Simulations of atmospheric variability induced by sea surface temperatures and implications for global warming. ***Science***, **266**, 632-634.

Kumar, A., M. P. Hoerling, M. Ji, A. Leetmaa, and P. D. Sardeshmukh, 1996: Assessing a GCM's suitability for making seasonal predictions. *J. Climate*, **9**, 115-129.

755-793.

Lau, N. -C., and M. J. Nath, 1994: A modeling study of the relative roles of tropical and extratropical SST anomalies in variability of the global ocean-atmosphere system. *J. Climate*, **7**, 1184-1207.

Levitus, S., Antonov, J., Boyer, T., and Stephens, C., 2000: Warming of the world ocean. *Science*, **287**, 2229–2234.

Reynolds, R.W., and Smith, T. A., 1994: Improved global sea surface temperature analysis using optimum interpolation. *Journal of Climate*, **7**: 929-948.

Wallace, J. M., C. Smith, and Q. Jiang, 1990: Spatial patterns of atmosphere-ocean interaction in the northern winter. *J. Climate*, **3**, 990-998.

Yulaeva, E., and J. M. Wallace, 1994: The signature of ENSO in global temperature and precipitation fields derived from the Microwave Sounding Unit. *J. Climate*, **7**, 1719- 1736.

Figure Captions

Fig. 1. Time-latitude section of the observed zonally averaged monthly 200 hPa height anomalies (left panel, contour interval 10m), and time-longitude sections of the 10N-10S area averaged monthly precipitation (center panel, contour interval 1 mm/day), and SST (right panel, contour interval 0.5 standarized departure) anomalies. The period

of analysis is January 1997-January 2000. Rainfall anomalies are estimate from the OLR anomalies using Arkin and Meisner's (1987) empirical relation. SST anomalies have been normalized by the monthly standard deviation. Contours are smoothed with a 3 month running average.

Fig. 2 Observed 200 hPa height anomalies for the 12-month average of January 1999-December 1999. Contour interval is 10 m.

Fig. 3. Same as Fig 1., except the ensemble mean atmospheric GCM 200 hPa height (left panels, contour interval 10 m), and rainfall (right panels, contour interval 1 mm/day) based on the MRF9 (top panels) and CCM3 (bottom panels).

Fig. 4. Zonally averaged 200 hPa height anomalies averaged for January 1999-December 1999 for each of the 12 CCM3 simualtions that have been forced with the observed global SSTs of the period.

Fig. 5. Reconstruction of the time-latitude section of the observed (left panel), MRF9 (middle panel) and CCM3 (right panel) zonally averaged monthly 200 hPa height anomalies (left panel, contour interval 10m) based on the regression signal related to tropical east Pacific SST anomalies.

The period of analysis is January 1997-January 2000